was based on the apparent relationship between the rainfall of St. Louis and Oregon, Mo., and Omaha and North Platte, Neb., and the preceding March-May temperature of central Europe (Frankfurt, Königsberg and Bucharest). Extended to include 1875-1934, $r = -0.54$.

In 1935, 1936 and 1937 the temperature and subsequent rainfall departures were as follows:

Year	1935	1936	1937
Mean of temperature departure (C°), March-May at Frankfurt, Konigsberg and Bucharest, from normal, 8.9 C° (1875-1934)	—0.3	1.4	1.6
Departure of rainfall (in.) June-Aug. at St. Louis + Oregon + Omaha + North Platte, from normal, 42.7 in. (1875-1934)	—9	—22	—5

If forecasts had been made *simply as to sign*, two of them would have been right and the third would not have proven an altogether serious failure.

The Velocity of Sound Waves and the Temperature in the Stratosphere in Southern California*

By B. GUTENBERG

In 1904, G. von dem Borne investigated a region where an explosion of dynamite had been heard. He found that there were two distinct zones of audibility, one surrounding the source and another, separated from the first by a "zone of silence," at a greater distance. Many subsequent investigations[1] have shown that usually two or more zones of audibility result from explosions. Fig. 1 gives an example.

*Balch Graduate School of the Geological Sciences, California Institute of Technology, Pasadena, Contribution No. 272.

[1]For details see for example: B. Gutenberg, Die Schallausbreitung in der Atmosphäre. Handbuch der Geophysik, vol. 9, pp. 89-144 (1932).

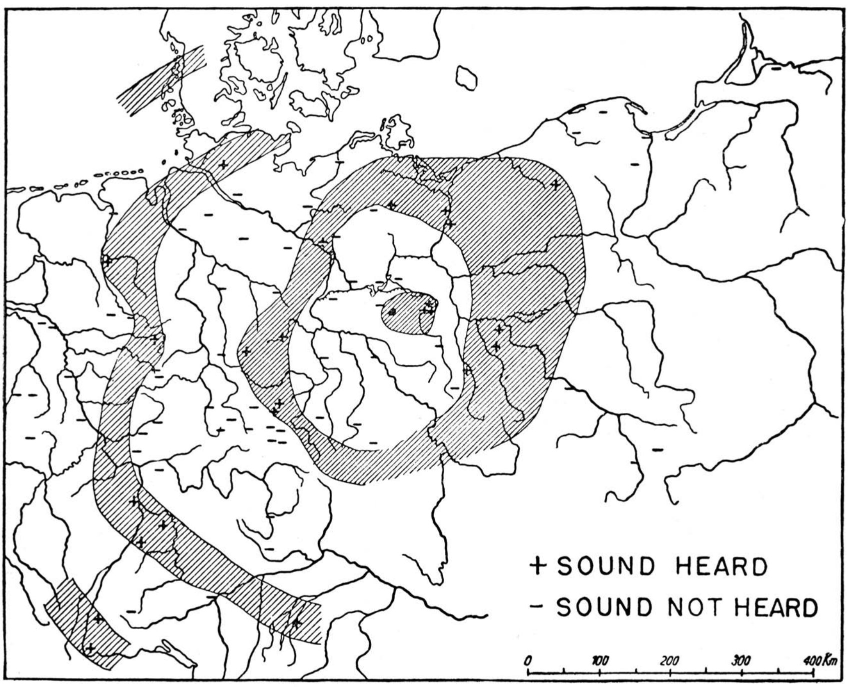

FIG. 1. Observations of sound after explosion of 5000 kg of ammunition, which was buried, on Dec. 18, 1925, 11 a. m. After Hergesell and Duckert.

During the last two decades, observations by ear have been supplemented by records from instruments of various types. If the travel times of these waves are plotted against distance, it is found that only in the inner zone do the times correspond to those calculated for the direct waves from the origin to the station, while for each successive zone the times are delayed by an amount which increases from zone to zone (Fig. 2). Usually

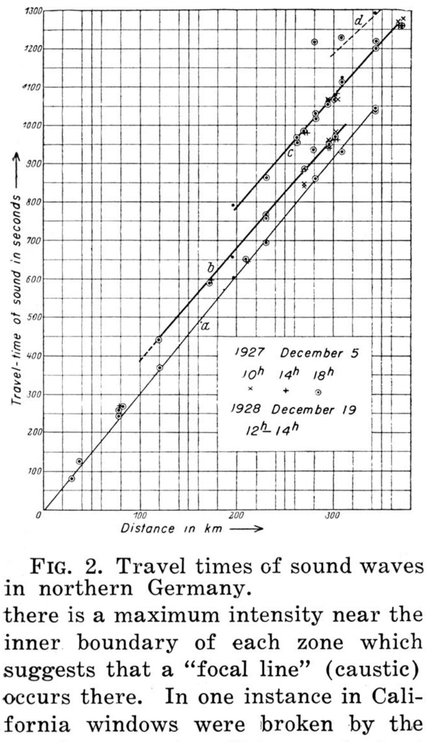

FIG. 2. Travel times of sound waves in northern Germany.

there is a maximum intensity near the inner boundary of each zone which suggests that a "focal line" (caustic) occurs there. In one instance in California windows were broken by the sound waves at a distance of about 240 km from the source, while at short distances little or no sound was heard[2]. In Europe, the distance of the first ring from the source has a yearly period with a minimum of of about 120 km in February and a maximum of about 220 km. in August. The deviations of the observed travel times from the monthly average for a given point are, in general, much smaller than the amplitude of the yearly period. No cases of rapid changes during a day seem to have been found thus far.

The data, especially the observed travel times, have led to the conclusion that the sound waves which arrive at the second and succeeding zones have traveled through the stratosphere and that their velocity at the highest point of their path exceeds the velocity of sound near the ground. Fig. 3 shows paths of the sound waves for an average case in Europe under the assumption that the temperature does not change horizontally. The inner boundary of the ring is determined by the ray through the stratosphere which arrives at the shortest distance. It need not be the ray which leaves the source horizontally (which is indicated in the figure by a full line), but may leave the source at a smaller angle of incidence (barred line in the figure). In this case, the inner boundary is a focal line, which corresponds to the observations. The

[2]B. Gutenberg and C. F. Richter, Pseudoseisms caused by abnormal audibility of gunfire in California. Gerlands Beitr. zur Geophysik, vol. 31, pp. 155-157 (1931).

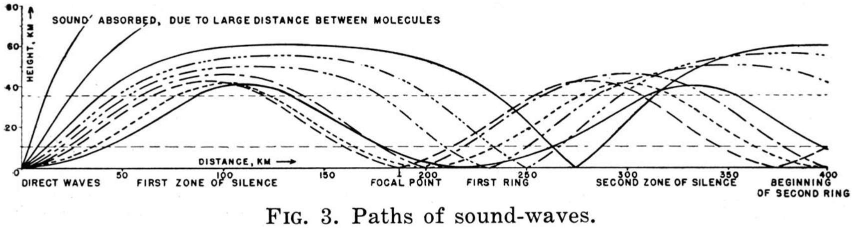

FIG. 3. Paths of sound-waves.

outer boundary of the zone is fixed by the rays which have their highest points between 60 and 70 km above the ground. As Schrödinger has shown no sound can be transmitted at greater heights because the distance between the molecules are too large there. The outer zones of audibility are produced by rays which have been reflected twice, three times, etc., at the surface of the earth. The observed travel times agree very well with this hypothesis.

By far the most numerous data on these sound waves consist of observations in Europe at about 53° N. lat. However, there are some data from Nova Zembla, most of them from about 77° N.[3] All show the same general facts; the indirect sound waves (observed in the ring zones) are heard more frequently and more strongly to the east of the source during winter, to the west during summer. The times of transmission (travel time) to the rings is about equal in central Europe and in Nova Zembla; for the first ring it is about half a minute shorter in late summer than in late winter.

Additional data are now available from Southern California, about 33° N. lat. Since October 1937, a sensitive instrument for recording changes in air-pressure has been in operation at the Seismological Laboratory in Pasadena. The instrument was designed by Dr. H. Benioff, who will describe it more fully elsewhere. He gives here the following short description of the instrument:

"The responding element consists of a permanent magnet moving-conductor type loudspeaker mounted in one of the sides of a sealed container of approximately one-fifth cubic meter capacity. The effective diameter of the loudspeaker cone is six inches. The natural period of vibration of the cone assembly is approximately 150 cycles per second. Hence for frequencies less than 50 cycles per second the cone-displacement is proportional to the atmospheric pressure increment and the electromotive force induced in the coil is proportional to the rate of change of atmospheric pressure. The output-currents are recorded on a standard seismograph recorder having a galvanometer of 0.25-second period, somewhat overdamped and a drum-speed of one mm. per second at the periphery."

Since its installation, this instrument repeatedly has recorded sound waves originating from gun fire during target practice by the United States Navy. For about 130 separate time periods on 17 days between Nov. 9, 1937 and Jan. 11, 1938 and between Aug. 30 and Nov. 3, 1938, Captain H. Leary, U. S. Navy, has kindly furnished the locations of the firing ships (which were approximately south-south-west of Pasadena) to the nearest minute in longitude and latitude, and the time of beginning of firing to the nearest minute. Only through this cooperation of the U. S. Navy was this investigation made possible. The meteorological data for the area under consideration were provided through the courtesy of Dr. I. Krick, of the California Institute of Technology, including the upper air data recorded at the airport of Burbank (about 12 km west of Pasadena) and at San Diego. In only a few instances the travel times of the waves are close to the times calculated for the direct wave considering the given temperature and wind. In most instances by far they are about 1½ min. too late, indicating that they arrived along an indirect path.

As the sound waves were known to be recorded occasionally by the short-period Benioff seismographs, the records of the auxiliary stations connected with Pasadena were searched for the days under consideration. The

[3]K. Wölcken, Schalluntersuchungen im Polargebiet. Zeitchr. f. Geophysik, vol. 10, pp. 22-234 (1934).

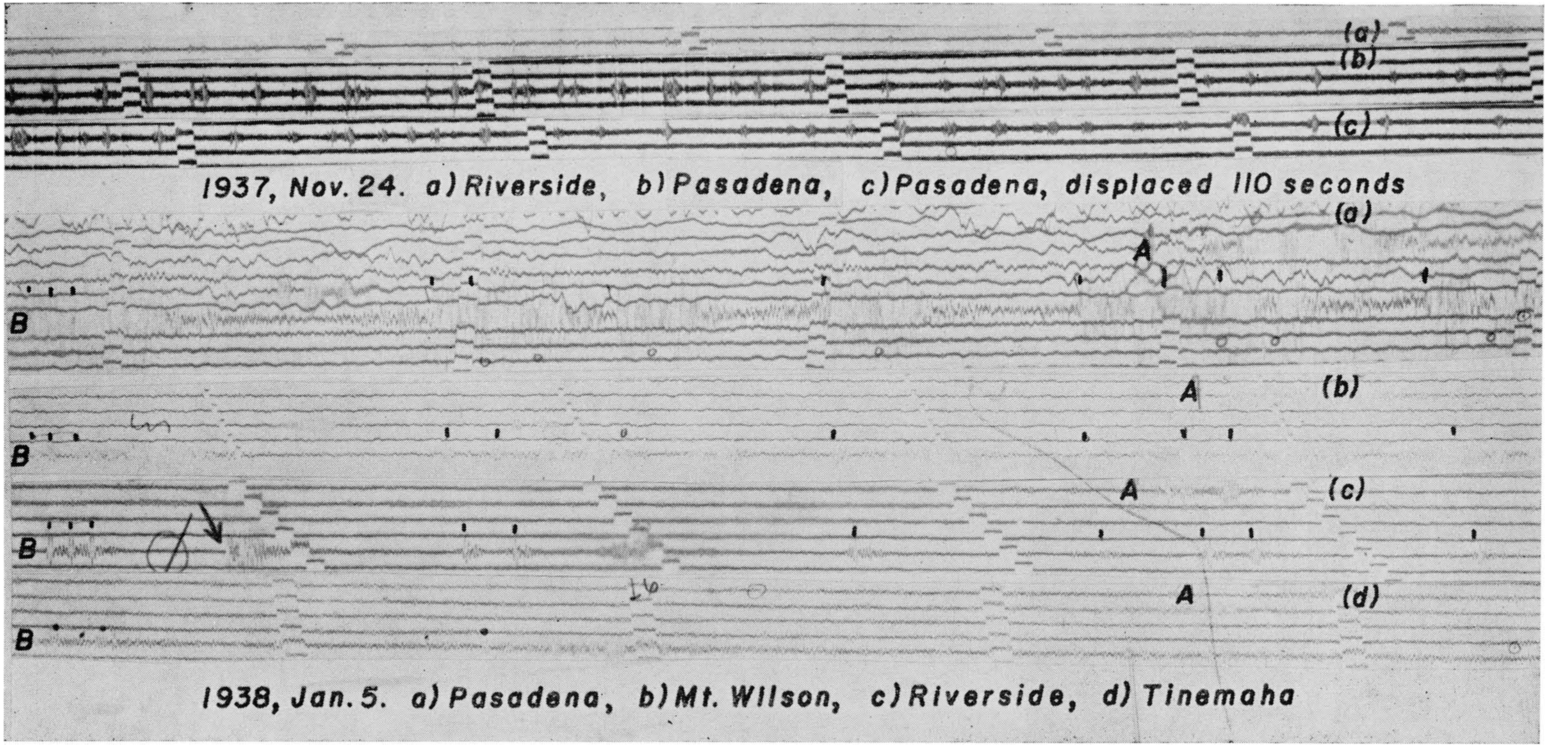

FIG. 4. Records of gun fire in southern California; at Pasadena by Benioff barograph, others by short period vertical Benioff seismograph. The interval between two succeeding marks is one minute. The time interval between one line and the next is approximately 15 min. On the originals, 1 mm corresponds to 1 sec. Distances from the source: upper curves, Pasadena, 121 km; Riverside, 163½ km; lower curves A, Pasadena, 205 km; Mt. Wilson, 218 km; Riverside, 285½ km; Tinemaha, 516 km; B, Pasadena, 171½ km; Mt. Wilson, 187 km; Riverside, 211 km; Tinemaha, 484 km. The recorded waves at Riverside, following the arrow after "B" were produced by a small local earthquake.

records of La Jolla and Haiwee were too much disturbed by local causes which produce movements similar to those caused by gun fire. However, the records of all other stations showed in some instances clear evidence of recorded sound waves. The excellent correlation may be seen from Fig. 4. The coordinates of the stations are as follows:

Station	N. lat.	W. long.	Elev. m
Pasadena	34° 09′	118° 10′	295
Mt. Wilson	34° 14′	118° 03′	1742
Riverside	34° 00′	117° 23′	250
Santa Barbara	34° 27′	119° 43′	100
Tinemaha	37° 06′	118° 16′	1180

It seems very likely that the sound waves did not affect the instruments directly, but produced vibrations of the ground and the buildings which, in turn, were recorded.

The comparison of the times of arrival of the sound waves at two or more stations permits the exact calculation of the "apparent velocity" between any two stations; however in general the uncertainty of the absolute time, due to the fact that the time of firing was given only to the nearest minute, can not be removed. There are three exceptions: for eight instances on Dec. 14, 1937, between 8 a.m. and 11 a.m. the time of firing was given to the nearest 0.1 min. On Jan. 11, 1938, the times were given to the nearest minute. However, the probable origin time could be calculated in the following way. The sound waves arrived at Santa Barbara more than one minute earlier than at Pasadena although Pasadena was 20 km closer to the source. This made it very probable that the first waves recorded at Santa Barbara were direct waves whereas the record at Pasadena began with the indirect waves. Using the known sound velocity for direct waves, the origin time of the sound waves could thus be calculated from the time of arrival at Santa Barbara. It was about 36 sec. later than that given by the Navy. A similar case happened on Nov. 24, 1937, when the first sound waves arrived 3¾ min. earlier at Pasadena than at Riverside which in this case was 42½ km more distant from the source than Pasadena. A careful comparison shows that, besides the direct waves, the indirect waves, too, were recorded at Pasadena, as may be seen in the upper part of Fig. 4. The second and the third record in this figure are the same; however, the third is displaced by an amount corresponding to 110 sec. The good correlation of the two records indicates that the indirect waves arrived at Pasadena about 110 sec. later than the direct. It must be considered, of course, that only the direct waves in the first record and the indirect of the second must coincide. The calculated time of firing was 1 min. 7 sec. earlier than that given by the Navy.

In each of these three instances, all available impulses have been measured and compared. The differences between the stations show excellent agreement and rarely differ by more than 2 sec. between succeeding impulses. However, they change gradually with time; this is probably due to changing conditions in the air (temperature, wind) as well as to the movements of the ships. The resulting travel times have been plotted in the lower part of Fig. 5 as a function of the distance. The results from Tinemaha (distance 482 km) have been added with dots under the assumption that the impulse is due to a once reflected wave and also that it is due to twice reflected waves.

If the temperature of the air is known ($T=$ absolute temperature) the velocity, V, of the sound waves can be calculated:

$$V = \sqrt{101.32\, a\, Tk/d_0}$$

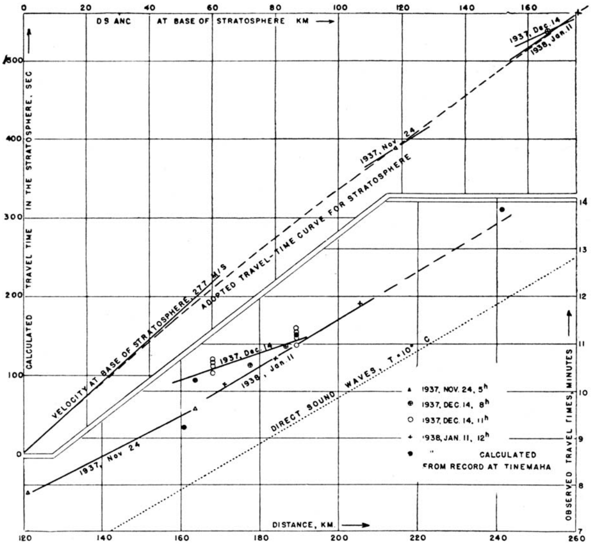

FIG. 5. Lower part: travel times (source-station) of sound waves in southern California. Upper part: calculated travel times of sound waves in the stratosphere corresponding to the data below.

where a = coefficient of thermal expansion, k = ratio of specific heat under constant pressure to specific heat under constant volume, and d_0= the density of the gas at sea level. The equation supposes that the process is purely adiabatic. As far as laboratory experiments are available, the values of a and k do not differ much under the conditions prevailing in the part of the atmosphere under consideration; at least up to 30 km, and, probably, much higher, the composition of the air does not change noticeably, so that d_0 is practically constant. Consequently, equation (1) reduces to $V = 20.1 \sqrt{T}$ (1a)

Fortunately, the wind velocity was small in most instances and did not increase very fast with height (maximum, on Dec. 14, NNE 15 m/sec. at 4 km elevation, not known above, on other days smaller). Neglecting the wind, the travel times t_s and the distance Δ_s for the section of the ray in the stratosphere can be calculated by subtracting the distance D^* and time t^* in the troposphere from the total distance Δ and the observed travel time t:

$$D^* = 2\int_0^H \tan i \; dh$$

$$\Delta_s = \Delta - D^*$$

$$t^* = 2\int_0^H \frac{1}{V \cos i}\, dh \qquad (2)$$

$$t_s = t - t^*$$

H is the height of the base of the stratosphere, i is the angle of incidence (angle between ray and plumb line) of the waves as a function of the height h, and V the sound velocity there as given by equation (1). For a given ray the angle i is given as a function of h by:

$\sin i = (V/V_0) \sin i_0 = V\,(\delta t/\delta\Delta)_0$ (3)

Δ = distance from the source to the point where the ray returns to the ground and t = corresponding travel time. The indices "o" indicate that the corresponding quantities including the derivative have to be those found for sea level, whereas i and V refer to the elevation h (see above).

If the temperature T decreases in the troposphere with height, as it happens usually, it follows from (1a) that the veloccity of sound waves must decrease correspondingly, so that in equation (3) V is smaller than V_0, and, consequently, i is smaller than i_0. This means that the rays are curved upward. A true "direct" sound wave through the troposphere is only possible if either the wind increases with height, thus bending the rays down in the direction of the wind or the temperature increases with height near the ground, or both conditions are fulfilled. Another consequence of equation (3) is that the sound waves (direct or indirect) are likely to have larger amplitudes in those sectors around the source where the temperature is lower than that at the source; the angle of incidence, i, in this case is smaller at the station than at the source; the rays arrive more from above. If the temperature is higher at the station, it easily may happen that

$$(V/V_0)$$

$\sin i_0$ is larger than 1 for all rays coming down in the region of the station, as i_0 is usually close to 90° (see Fig. 3). In this case no rays reach the ground in the relatively warm region, but each ray turns upward again at that level where $V = V_0/\sin i_0$ or $T = T_0/\sin^2 i_0$. As a consequence, the zones of audibility are usually better developed in the cold sectors around the source than in the warmer sectors unless the wind has an adverse effect. As has been mentioned, in western Europe (and, probably, in California) the sound is better heard to the west of the source during summer and to the east of the source during winter. The effect of the wind, in general, acts in the same direction as has been pointed out by Whipple, and frequently is even larger than that of the temperature.

In the three cases used in Fig. 5, the change of temperature with height did not differ much. On the average, the temperature was between 10°C. and 15°C. from the ground to an elevation of 1 km, then decreased slowly, passing the freezing point near 3 km, reaching –10° at about 5 km, and continued to decrease to the highest point reached by the instruments. On Jan. 12, 1938, the temperature found at Burbank at an elevation of 15 km was –75°C., and there was no indication that the stratosphere had been reached. However, this must have been close to the stratosphere. For the calculations, it was assumed that the stratosphere began at 16 km and that the temperature there was –83°C. (190° abs.). The following data correspond to Fig. 5 and the temperature just mentioned:

Date 1937/38	Δ km.	From Fig. 5 t m	s	$(\delta\Delta/\delta t)_0$ m/sec	eq. 1 V_0 m/sec	eq. 3 $\sin i_0$	$\sin i_s$	Δ_s km.	eq. 2 t_s m	s
Nov. 24	140	8	36	390	340	.61	.50	118	6	30
Dec. 14	180	10	52	550	340	.44	.36	166	8	58
Jan. 11	200	11	30	370	342	.65	.53	176	9	21

The index "o" indicates that the corresponding quantity is to be taken at sea level, while the index "s" refers to the base of the stratosphere. The values of the last columns furnish the travel time curve for rays beginning and ending at the base of the stratosphere. The direction of this curve at the beginning is given by $(\delta\Delta/\delta t)_0 = V_s$, which is 277 m/sec, if the temperature is –83°C. These data have been plotted in the upper part of Fig. 5; a smooth curve can be passed through the points. It is possible to calculate the highest point of a ray, beginning at the base of the stratosphere and ending there at a distance Δ, by the integration method which is used for the same purpose in seismology and was developed by Herglotz, Wiechert and Bateman. If $V^* = \Delta\delta/\delta t$ (apparent velocity) at the given distance Δ^*, and V_Δ its value at the variable distances from O to Δ^*, the elevation H^* of the highest point of the ray ending at Δ^* is given by

$$H^* = \frac{1}{\pi} \int_0^{\Delta^*} q \, d\Delta^* \text{ where } \cos q = V^*/V_\Delta \qquad (4)$$

The application of this method supposes that the wave front is perpendicular to the rays and that the velocity does not decrease with height. The first requirement is not fulfilled if the wind bends the rays; however, in general this effect is small. The second condition requires an increase in temperature with height. So far as the observations indicate, this occurs for California about December agree with those found for central Europe in summer. Unfortunately, no exact data are available yet for southern California during late winter and summer.

The hypothesis that the increase in the velocity of the sound waves in the stratosphere is caused by a corresponding increase in temperature

Δ km	t sec	V m/sec	H^* km	h km	V m/sec	temperature abs.	°C
0	0	277	0	17	277	190	–83
50	178	298					
100	337	326	12½	29½	326	264	–9
150	485	349	21½	38½	349	303	30
200	624	370	31½	48½	370	337	64

in general in our region. The velocity at the highest point of the ray is given by the value of $\delta\Delta/\delta t$ at the distance Δ^*. The following table gives the assumed fundamental data, taken from the upper part of Fig. 5, and the results; as the base of the stratosphere has been assumed at 17 km, we have $h = H^* + 17$ km.

The data of the two last columns have been found on the supposition that equation (1a) can be applied. The results have been plotted in Fig. 6, together with similar values calculated for Europe[4]. The values found with height was first suggested by Whipple in 1923 (Nature, vol. 111, p. 187). The first calculated values were published independently by Gutenberg and by Wiechert at a meeting (Deutsche Geophys. Ges.) in Dec. 1925. Although Gutenberg supposed a scheme similar to that given in Fig. 3, while Wiechert made the assumption that the inner boundary of the first ring is given by the rays leaving

[4]B. Gutenberg, Schallgeschwindigkeit und Beitr. z. Geophysik, vol. 27, pp. 217-225 (1930) Temperatur in der Stratosphäre. Gerlands Beitr. z. Geophysik, vol. 27, pp. 217-225 (1930) —vol. 35, pp. 46-50 (1935).

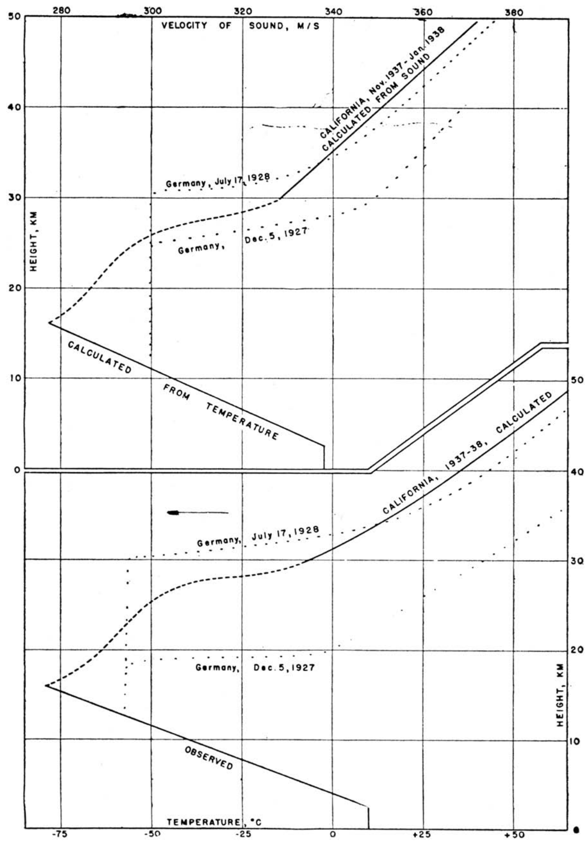

FIG. 6. Upper part: velocity of sound waves in southern California calculated from the data in Fig. 5; results for northern Germany for comparison. Lower part: temperatures corresponding to the velocities in the upper part of the figure under the assumption that equation (1a) is correct.

the source horizontally, the results agreed fairly well. In the interim, calculations on the temperature of the stratosphere considering the effects of the absorption of the solar radiation in the water vapor and ozone of the atmosphere gave results similar to those which have been derived from the study of the sound waves[5]. In Europe, the minimum height of the base of the warm part of the stratosphere (minimum distances of the zones of indirect sound waves) occurs late in winter and coincides approximately with the time of year when the amount of ozone in the atmosphere has its maximum[6].

The conditions at elevations above 60 km, where no sound waves can be propagated, are not well known; at

[5]See, for example, Conference on atmospheric ozone. Q. J. R. Met. Soc. vol. 62 (1936). suppl.

[6]See, for example, C. L. Pekeris, Atmospheric ozone as a possible meteorological factor. Bull. Amer. Met. Soc., vol. 20, p. 4 (1939).

levels between 60 and 90 km the temperature may or may not decrease. At elevations of 100 km and above, the greater number of the calculations based mainly on the behavior of radio waves indicate temperatures noticeably higher than those found from the sound waves for 60 km altitude.

Various alternative hypotheses have been suggested to explain the increase in velocity of the sound waves in the stratosphere. The assumption that the increase in velocicty is due to a rather rapid increase in the amount of light gases (decrease in d_0, eq. 1) has been disproved by the observations of the composition of the air up to about 30 km, which showed no appreciable change with height. The hypothesis that the wind is the main cause was disproved by the occasional observation of full rings around the source (Fig. 1), and by the finding that the travel times to two points at the same distance in opposite directions from the source are about equal. The main alternative explanation which remains is based on the possibility that equation (1) is no longer correct at altitudes above 30 km. However, no definite reason has yet been given. Finally, it has been suggested that the change in pressure due to the sound wave is large as compared with the pressure itself at the elevations where the high velocity is found, and that processes similar to those near the source of an explosion produce the high velocity. However, the fact that no difference has been found between the waves produced by small explosions and those from the very largest seems to contradict this assumption.

SUMMARY

Sound waves from gun fire in southern California, about 33° N. lat., show travel times similar to those observed in Europe and Nova Zembla. It is concluded that the increase in temperature at an elevation of about 30 to 40 km is approximately the same in the three regions mentioned.

Shorter Contributions

Cross-Country Dust

The extreme dryness of the central plains this spring, that so greatly curtailed the winter-wheat crop, was brought visibly to the attention of people on the North Atlantic seaboard when clouds of dust from the parched fields were carried more than 1000 miles to the coast. Though some western dust must often reach the eastern states unrecognized, there are times, as on April 24 and May 11, 1939, when the grayish haze, greatly reduced visibility, weakened sunshine, the accumulation of a thin layer of dust, and the smarting of the eyes, makes its presence readily noticeable.

The cloud of May 10-11 was picked up on the plains by a strong westerly wind on the 10th, elevated, and transported rapidly to the northeastern states, where it reached central Pennsylvania before daybreak (report from Dr. H. Landsberg) and southern New England by 9 a.m., when first noticed at Blue Hill. The sunshine was reduced 50% from its clear sky value of the day before and the visibility from 50 to only 5 miles. The dust began to clear by late afternoon, and the following day was as fine as the 10th had been.

Northern New England was outside the trajectory of the dust cloud. Mt. Washington had very clear air that morning, but to the southeast at 10:30 the murky air over southern New England was visible. The dust haze reached a height of 5 to 10° above the horizon in that direction, indicating that the top of the dust cloud was